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Hardness Prediction for the Repair Welding of 2.25Cr-1Mo Pressure Vessels

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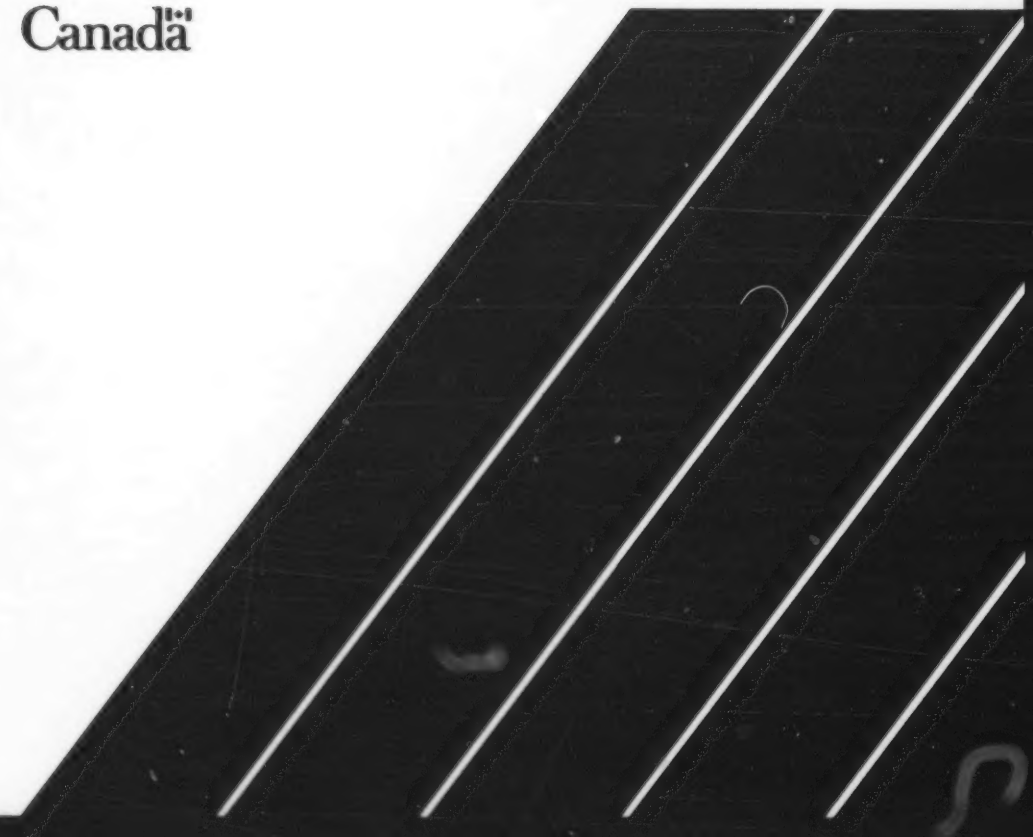

METALS TECHNOLOGY LABORATORIES

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HARDNESS PREDICTION FOR THE REPAIR WELDING OF 2.25Cr-1Mo PRESSURE VESSELS

by

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ABSTRACT

Alberry (1) has developed a set of empirical rules predicting the hardness after each pass in multipass welds made in SA508 Class 2 steels. This algorithm has been used to predict the number of layers required to achieve desired hardnesses. A transformation and tempering algorithm for 2.25Cr-1Mo, similar to that of the above steel is presented.

The tempering algorithm of Alberry which suffers from several minor problems has been modified. A mathematically correct method for the calculation of the tempering occurring in an anisothermal cycle is demonstrated. In addition, the rules used to relate the softening that occurs during tempering are heuristic. Separate rules are proposed for the kinetics of softening depending on the peak temperature. A re-examination of those rules reveals that they can be recast in the form of a single rule for the material examined. Reassessing the basic data presented by Alberry leads to a single softening rule with better theoretical justification.

LABORATOIRES DE LA TECHNOLOGIE DES MÉTAUX
RAPPORT MTL 90-42(TR)

PRÉDICTION DE LA DURETÉ DES SOUDURES DE RÉPARATION SUR LES RÉCIPIENTS SOUS PRESSION EN ACIER 2,25Cr-1Mo

par

A.S. Oddy et R.S. Chandel

RÉSUMÉ

Alberry (1) a élaboré une série de règles empiriques permettant de prédire la dureté après chaque passe dans les soudures multipasses réalisées sur des aciers SA508, classe 2. Cet algorithme a été utilisé pour prédire le nombre de couches requises pour obtenir la dureté désirée. Un algorithme de transformation et de revenu pour l'acier 2,25Cr-1Mo, similaire à l'algorithme susmentionné, est présenté.

L'algorithme d'Alberry, qui présentait plusieurs problèmes mineurs, a été modifié. Une méthode mathématiquement correcte de calcul du revenu se produisant dans un cycle anisothermique est démontrée. Par ailleurs, les règles utilisées pour établir l'amollissement qui se produit pendant le revenu sont heuristiques. Des règles distinctes sont proposées pour la cinétique de l'amollissement en fonction de la température maximale. Un réexamen de ces règles révèle qu'elles peuvent être reformulées sous forme du'une règle unique pour le matériau examiné. Une réévaluation des donnés fondamentales présentées par Alberry conduit à l'établissement d'une règle d'amollissement unique qui se justifie mieux théoriquement.

INTRODUCTION

Reactor vessels used for the hydrotreating of heavy oils and tar sand bitumen are frequently made of 2.25Cr-1Mo steel in thicknesses of 150 mm to 300 mm. Defects developed during installation or service are often repaired by welding. For practical reasons post-weld heat treatment of the repair welds is undesirable. This has led to continued effort to develop weld repair techniques that do not involve post-weld heat treatment.

Repair welding attempts to fill the defect with successive weld passes in such a way as to normalize and temper previous passes and thus reduce the hardness to required values. Recently a six layer automatic GTAW technique has been proposed for the repair welding of nuclear reactor vessels made of SA508 Class 2 Steel (1). In this technique the second and third passes refine the microstructure of the first pass and the last three passes temper the first pass. Later, excess material can be ground off or left. In this technique the hardness of the first pass decreases with each successive pass. Bead thickness is controlled to ensure that the refining and tempering isotherms move upwards by the same distance as the bead thickness.

Alberry (2) has developed a set of empirical rules predicting the hardness after each pass. This has been incorporated in an algorithm that can be used to predict the number of layers required to achieve the desired hardness. The algorithm is based on data gathered for SA508 Class 2 steel (3). Since the transformation and tempering behaviour of 2.25Cr-1Mo is similar to that of the above steel, it is likely that this model may also work for 2.25Cr-1Mo steel repair welds. This report reproduces Alberry's model for the prediction of hardness in repair welds made 2.25Cr-1Mo steel. Modifications to the model to improve the tempering behaviour are also described.

The tempering algorithm of Alberry suffers from several minor problems and can be improved. Alberry converts the thermal history into an equivalent time spent at an arbitrary temperature, in this case 800°C. This conversion is unnecessary. Furthermore, the conversion method is flawed. A mathematically correct method for the calculation of the tempering occurring in an anisothermal cycle will be demonstrated. In addition, the rules used to relate the softening that occurs during tempering are heuristic. Separate rules are proposed for the kinetics of softening depending on the peak temperature. A re-examination of these rules reveals that they can be recast in the form of a single rule for the material examined. Reassessing the basic data presented by Alberry leads to a single softening rule with better theoretical justification.

DESCRIPTION OF ALBERRY'S MODEL

Alberry's model can be broken down into several parts. The first uses an analytical expression for 3D heat flow in a semi-infinite plate to obtain thermal histories for each pass. The particular analytical expression used assumes a point heat source of infinite intensity and material

properties that are not temperature dependent. Use of this equation requires that the thermal efficiency be adjusted in order to match the predicted and measured weld bead dimensions. Alberry recommends a thermal efficiency of 125%.

The use of an analytical equation for determining the thermal history is not an essential feature of the algorithm. Time-temperature histories could be obtained experimentally or through nonlinear transient finite element analysis or any other method. Hardness values depend on the peak temperature and cooling rate.

SINGLE PASS HARDNESS

From the peak temperatures for each cycle the untempered hardness is obtained for a set of empirical rules. A distinction must be made between single pass hardnesses and multipass hardnesses. The peak temperature experienced affects the eventual hardness in several ways. High peak temperatures, typical of those near the fusion boundary, produce coarse-grained microstructures of either martensite or martensite and lower bainite. The lower peak temperatures seen somewhat further from the fusion line but still in a region of complete austenitization produce a finer grained microstructure. The prior austenite grain size decreases with decreasing peak temperature. Peak temperatures in the range of 800°C to 900°C correspond to partial austenitization, producing microstructures typically found at the HAZ-base metal interface. Alberry describes the hardness of single pass microstructures by three rules.

for $Tpk < Ac_1$	$Hv = 202$	(1)
for $Ac_1 < Tpk < 1200°C$	$Hv = 0.633Tpk - 290$	(2)
for $1200°C < Tpk$	$Hv = 470$	(3)

where Tpk is the peak temperature in °C and Hv is the hardness. The values used by Alberry for Ac_1 and Ac_3 are the dynamic values; i.e., the rapid heating rates cause a retardation in the transformation to austenite. Alberry recommends values of 808°C for Ac_1 and 892°C for Ac_3.

MULTIPASS HARDNESS

HAZ hardnesses of multipass welds are somewhat more complex. Tempering of previously hardened material will alter the hardness. Reaustenitization and subsequent carbide dissolution and precipitation or grain growth will also affect the hardness. Again the peak temperature is the critical variable. In Alberry's model the hardness produced by multiple retransformation is given by:

for $Ac_3 < Tpk < 1200°C$	$Hv = 0.067(Tpk-Ac_3) + 449$	(4)
for $1200°C < Tpk$	$Hv = 470$	(5)

This rule is only invoked if at least one of the previous cycles experienced a peak temperature greater than 1200°C.

TEMPERING

Material whose peak temperature exceeds Ac_1 will either partially or fully transform to austenite and, on cooling, transform to martensite or a martensite/lower bainite mixture. Subsequent reheating by successive passes will temper the microstructure causing a reduction in hardness.

The degree of tempering that occurs is dependent on the time spent at the tempering temperature. The revelant parameter used to relate the degree of tempering to the time held at a specific temperature is the Larsen-Millar parameter, LMP.

$$LMP = (1.8T + 492)[20 + \log(t)] \quad (6)$$

where, T is the temperature in C and t is the time in hours.

In the algorithm described by Alberry, the thermal history is divided into a large number of discontinuous isothermal steps. Each step, an interval Δt is converted into an equivalent interval at 800°C. These equivalent intervals are summed in order to give an equivalent time at 800°C for the entire thermal history. This method implicitly assumes that LMP is a linear function of time. That is, at a constant temperature, an interval Δt causes the same change in LMP no matter what t is. Equation 6 clearly demonstrates that this is not true.

An estimate of the error present in Alberry's method for the calculation of LMP and the conditions under which it is most serious can be obtained by calculating LMP for a single step of arbitrary length at a constant temperature other than 800°C. Alberry breaks the thermal history into a large number of isothermal steps each only 0.1 s long, calculates equivalent intervals at 800°C and sums the values calculated. It can be shown that this creates an error in LMP of

$$Error = (1440 - 1.8T)\log(n) \quad (7)$$

where n is the number of 0.1 s steps at temperature T. There is no error when n is 1 or T is 800°C. The errors will be worst at low temperatures. Thus the error inherent in Alberry's algorithm for a single isothermal step of 0.5 h at 400°C is 3000 or about 13%. For 1 min at 500°C the error amounts to 6%. Alberry's algorithm overestimates the value of LMP for temperatures below 800°C.

Equation 6 is only valid when comparing the results for isothermal intervals. It does not imply that the error is zero if the thermal history is broken into a series of single 0.1 s isothermal

steps. The rate at which LMP increases for a given time spent at a given temperature depends on the current value of LMP. Thus the error is cumulative and worst for large numbers of time steps at lower temperatures. For typical thermal histories the error will be most serious for histories with peak temperatures of approximately 500°C. At higher temperatures LMP will grow rapidly and the error is small. At lower temperatures LMP grows very slowly and has little effect. For typical thermal histories with peak temperatures of approximately 500°C the error in LMP amounts to about 5%. The error may not be large for typical thermal histories, nevertheless the correct procedure for calculation of the LMP is not complicated and will be necessary if the algorithm is applied to post-weld heat-treatments.

The mathematically correct method is only slightly more complicated. Again, the thermal history is divided into many discontinuous isothermal steps, and an equivalent time at the beginning of each step is calculated. In this case however equivalent intervals are not summed. The algorithm is as follows:

1. For a step Δt long at temperature T convert LMP at the beginning of the step into an equivalent initial time according to

$$tn = 10^{[LMP/(1.8T + 492) - 20]} \quad (8)$$

This represents the time necessary at temperature T to achieve the current value of LMP. In effect, all of the previous history has been replaced by an interval of duration tn at temperature T.

2. The equivalent time at the end of the interval is simply

$$t_{n+1} = t_n + \Delta t \quad (9)$$

3. The value of LMP at the end of the interval is calculated as

$$LMP = (1.8T + 492)[20 + \log(t_{n+1})] \quad (10)$$

At very low temperatures tn can be so large that it exceeds the largest value possible in a digital computer. In such cases any realistic value of Δt will cause no appreciable increase in LMP. The situation is analagous to holding the material indefinitely at absolute zero. Additional tempering will not occur, LMP will not increase.

HARDNESS REDUCTION DURING TEMPERING

Alberry expresses the softening that occurs during tempering in the form of 3 rules which relate the current hardness to the LMP value for the thermal cycle. These 3 rules are required to differentiate between the response of materials with different initial hardnesses. All three rules show a parabolic response of hardness and LMP. There are some odd aspects associated with these rules.

All three rules show an increase in hardness occurring during the early stages of tempering, reaching a maximum hardness at an LMP of approximately 11,250, followed by a decrease in hardness. The hardness returns to its initial value at an LMP of 22,500, and continues to decrease until the hardness reaches its fully softened value of Hv = 202 at an LMP of about 40,000. The increase in hardness is unrealistic, an LMP of 11,250 corresponds to about 20 h spent at room temperature. It is merely a consequence of fitting a parabola to the experimental data.

Some of the basic data used by Alberry does show an increase in hardness at an LMP of 20,000. Alberry's experimental data for single pass hardness measurements show that initial hardnesses can vary by as much as Hv 50 for the same peak temperature. Since the actual initial hardness of every sample is not known it seems more likely that this apparent increase in hardness is due solely to the variability expected in hardness measurements.

Another difficulty lies in the response of material which has experienced a peak temperature of greater than 1200°C. According to the rules expressed by Alberry the hardness after welding would be Hv 470. According to the softening rules of Alberry, if this material is held at room temperature it immediately drops to Hv 435 and increases to Hv 480 after 20 h and then gradually decreases. All of these difficulties are minor, but can be eliminated. This will be particularly useful if the algorithm is ever incorporated in a finite element analysis (FEM) of the heat flow and residual stresses caused by welding.

If the 3 rules of Alberry are rearranged it is possible to show that there is in fact only 1 rule which governs the softening during tempering. If H_o is the initial hardness immediately after welding then the 3 rules can be restated as:

$$(H_o - H)/(H_o - 202) = B\text{x}LMP + A\text{x}LMP^2 \qquad (11)$$

In this form all 3 rules possess coefficients A and B which differ by less than 5% from

$$A = 1.6\text{x}10^{-9}$$
$$B = -3.6\text{x}10^{-5}$$

Thus it can be seen that the degree of tempering can be expressed by 1 rule which is independent of the initial hardness.

$$S(LMP) = BxLMP + AxLMP^2 \qquad (12)$$

This is obtained through a simple rearrangement of the rules stated by Alberry. This relation starts at zero and eventually reaches 1, indicating that the material is fully softened. The increase in hardness seen in the rules of Alberry for the initial stages of tempering still occurs. Increasing hardness is reflected by negative values for S.

Given that 1 law appears to govern the degree of tempering regardless of the initial hardness it is possible to reassess the relation describing S in order to avoid the spurious increase in hardness. The hardness values of Alberry were extracted and the degree of tempering computed (3). The results are shown in Fig. 1. Two curves are also shown. The first is the parabolic relation of Alberry which shows an initial increase in hardness as S becomes negative. The second curve is the line of best fit of the form

$$S(LMP) = C\, e^{(LMP/D)} \qquad (13)$$

where, C = 0.0016 and D = 5610.

The scatter in the experimental results is larger than desired. This is no doubt due to the use of initial hardnesses. The hardnesses listed by Alberry are unlikely to be all for the same sample, before and after tempering. It also no doubt accounts for those cases where negative values were obtained. It does demonstrate that a parabolic softening relation is not necessary.

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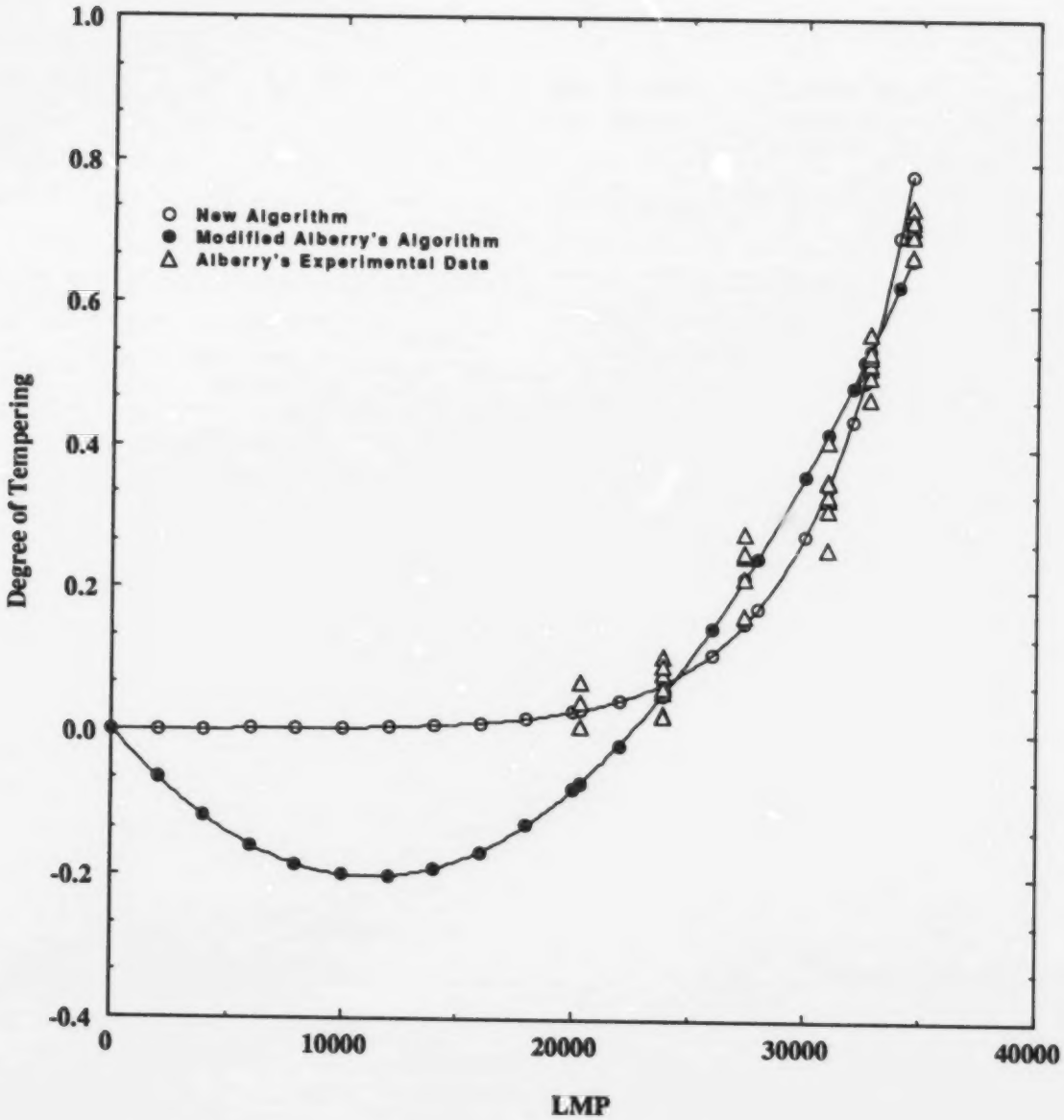

Fig. 1. Relationship between LMP and degree of tempering.